NISTIR 4660

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September 1991

DEPARTMENT OF COMMERCE ★ UNITED STATES OF AMERICA ★

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MECHANICAL PROPERTIES AND FRACTURE TOUGHNESS OF AAR TC128 GRADE B STEEL IN THE NORMALIZED, AND NORMALIZED AND STRESS RELIEVED CONDITIONS

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ABSTRACT

Traditional mechanical property tests, ultimate and yield strength, reduction in area, elongation, impact, and the nil-ductility temperature were performed on AAR TC128 grade B steel in the normalized, and the normalized and stress relieved conditons from -51 C to room temperature. In addition the crack initiation fracture toughness, as function of temperature, was determined using crack tip opening displacement (CTOD) and J integral test procedures. The crack arrest fracture toughness, as a function of temperature were also determined. It was found that the normalized and stress relieved steel had overall better mechanical and fracture toughness properties than the normalized steel.

INTRODUCTION

As of January 1, 1989, normalized AAR TC128 grade B steel is required to be used for appropriate tank cars that carry hazardous commodities. The steel is normally identified as a carbon/manganese type with improved tensile and impact properties compared with those steels previously used. In order to provide a comprehensive mechanical property and fracture toughness database for ascertaining the structural integrity of this steel, the Mechanical Properties and Performance Group of the National Institute of Standards and Technology (NIST) was asked by Ms. Claire Orth, Chief of the Safety Research Division of the Federal Railroad Administration, to develop this database for TC128 grade B steel in both the normalized, and normalized and stress relieved conditions.

MATERIAL

Four plates each, 1.4 cm (9/16 inch) in thickness by 183 cm (72 inch) by 183 cm (72 inch) were made by Bethlehem Steel Corporation according to Association of American Railroads (AAR) specification TC128 for grade B, flange quality steel. The plates were purchased from the Bethlehem Steel Corporation, through Union

Tank Car Company (UTC), with the help of Mr. Thomas Dalrymple, chief engineer of UTC. Appendix I shows Bethlehem Steel's Test and Analyses report with the chemistry and metallurgical particulars for the plates. The plates were supplied in the normalized condition. Inclusion shape control was not used in the preparation of these steel plates. The sulfur content was to be not less than 0.010 weight percent.

TEST PROGRAM

The test program consisted of evaluating the traditional mechanical properties, i.e., ultimate, yield etc. and fracture toughness, i.e., J integral, CTOD, etc. of the steel in both the normalized, and normalized and stress relieved conditions. The four plates, upon arrival at NIST, were coded "I, J, K, and L," and plate "I" was used for all test specimens. A section was removed from the plate and the chemical composition was determined. Prior to the removal of the test specimens from the plate, metallographic specimens were sectioned from the plate in order to determine the as-polished and etched microstructures, the ferrite/pearlite grain size, and the predominant rolling direction. A section of plate "I" was also stress relieved, according to the AAR Specification M-128, at 635 C (1175 F) for one hour. Photomicrographs were taken of the normalized and stress relieved microstructure in the etched condition.

Standard American Society for Testing and Materials (ASTM) tensile specimens with a reduced diameter of 6.4 mm (0.250 inch) were prepared from the 1/4 thickness position in the plate according to ASTM Method A 370 - 90. Tensile specimens were tested at -51 C (-60 F), -40 C (-40 F), -29 C (-20 F), -18 C (0 F), and 22 C (+72 F). The tensile tests were conducted in an environmental chamber where the test temperature was held to ± 2 C. The impact properties were determined as a function of temperature using ASTM Method E 23 - 88, and the nil-ductility transition temperature was determined according to ASTM Method E 208 - 87a. In order to determine the ability of the steel to resist crack initiation, J-integral tests were conducted according to ASTM Method E 813 - 89. For comparison purposes, the fracture toughness using the crack-tip opening displacement was determined using ASTM Method E 1290 - 89. Having determined the ability of the steel to resist initiating a crack, the ability of the steel to arrest a propagating crack in the same steel was determined using ASTM Method E 1221 - 88. The test temperatures used in the fracture analysis were the same as those used in the tensile study.

RESULTS

Chemical Composition

Two check chemical analyses, along with the composition reported by the Bethlehem Steel Corporation and that required by the AAR specification are shown in Table 1. The chemical composition was within the allowable limits.

Metallographic Examinations

Prior to the removal of test specimens from the plate, the rolling direction was determined. Figure 1 shows photomicrographs of the normalized steel in three orthogonal directions in the as-polished condition. The photomicrograph

with the micron marker was determined to be the L-T orientation as defined by ASTM. The predominant rolling direction is shown by the arrow in the photomicrograph. Appendix II shows the ASTM's the crack plane orientation code for the test specimens.

This same sample was etched and the resulting microstructure at the 1/4 thickness location is shown in Figure 2. The microstructure consisted of regions of pearlite (black) dispersed throughout the ferrite (white). Grain size measurements conducted on the etched specimen according to ASTM Method E112 - 85 revealed that the ferrite/pearlite grain size was G.S. 12, or 5.6 μm. It is recognized that the higher the grain size number, the finer the ferrite/ pearlite grain size, and hence the better the mechanical properties of the steel.

Photomicrographs were taken of the normalized plate to show the variation in microstructure that existed throughout the plate. Figure 3 shows the overall microstructure and that observed at both at the centerline and quarter thickness locations within the plate. This variation in microstructure from the outside to the inside of the plate is not uncommon, and it is often referred to as "banded microstructure". Microstructural banding usually develops during the refining process of steel and is manifested after the rolling operation. Banding is thought to be the result of elemental segregation in the steel, primarily manganese. It should be noted that the mechanical properties of the banded areas could be different than those of the unbanded areas. To circumvent this potential problem, test specimens were taken from the 1/4 thickness location in the plate when possible.

For comparison purposes, two samples that were stress relieved at 635 C (1175 F) for one hour were polished and etched. These two samples represented the ASTM L-T and T-L orientations. Figures 4 and 5 show the microstructures observed at the edge, and the centerline of these samples. The microstructural constituents were similar to those observed for the normalized material; pearlite dispersed throughout the ferrite. However, an extensive amount of large, blocky pearlite (dark constituent) was observed along the centerline of both samples.

MECHANICAL PROPERTIES

Tensile

The ultimate tensile strength (UTS) results for both conditions are shown Tables 2, 3, 4, and 5 and plotted as a function of test temperature in Figure 6. Over the entire test temperature range, the UTS for the as-received normalized specimens taken from the L-T orientation was greater than those found for any of the other specimens, regardless of orientation or stress relief. The lowest ultimate tensile strengths, again over the entire test temperature range, were observed for the normalized and stress relieved T-L tensile specimens. The values are representative of a typical TC128 grade B steel.

The 0.2% offset yield strength (YS) results are shown in Tables 2, 3, 4, and 5 and plotted in Figure 7. The normalized, and the normalized and stress relieved yield strengths for the L-T orientation were found to be greater than

those similar specimens tested from the T-L orientation. The YS for the normalized, and normalized and stress relieved specimens taken from the T-L orientation did not follow the same trend with temperature as the UTS decreased. The YS was essentially the same from room temperature to about -18 C (0 F), then it abruptly increased, as was expected. This probably is an orientation effect, perhaps due to inclusion orientation.

Both the UTS and YS results are probably governed by inclusion orientation within the plate. More energy, i.e., load, is required to fracture a specimen when the inclusions lie parallel to the applied load as in the L-T orientation. When the inclusions lie perpendicular to the applied load, as in the T-L orientation, less energy is required to separate the inclusions, hence the load required to fracture the specimen is reduced.

The reduction-in-area (RA) results for both conditions are shown in Tables 2, 3, 4, and 5 and plotted in Figure 8. The RA values for the normalized and stress relieved specimens, tested from -51 C (-60 F) to 10 C (50 F) and taken from the L-T orientation, were greater than those obtained for the other specimens. It appears that ductility of the specimens tested from the T-L orientation, in terms of the reduction-in-area, is enhanced by stress relieving at 635 C (1175 F) for one hour.

Similar trends, like those observed for the UTS, YS, and RA, were not observed for the elongation results shown in Tables 2, 3, 4, and 5 and plotted in Figure 9. The elongation for the normalized and stress relieved specimens taken from the T-L orientation, over the test temperature range, was greater than for the other specimens. Again, normalizing and stress relieving the steel appears to enhance the ductility.

Charpy V-Notch Impact

The Charpy V-notch (CVN) impact test results for the normalized steel are shown in Tables 6 and 7, and plotted in Figure 10. As expected due to inclusion effects, the CVN values for the normalized specimens taken from the L-T orientation were found to be greater than those taken from the T-L orientation. The impact energies at the lowest test temperature, -51 C (-60 F), were found, on the average, to be about 77 J (57 ft-lb) for specimens tested from the L-T orientation and 29 J (22 ft-lb) for those tested from the T-L orientation. The upper shelf energy for specimens tested from the L-T orientation was found to start at about 4 C (+40 F) with an energy of about 169 J (125 ft-lb), whereas the upper shelf energy, for specimens tested from the T-L orientation, started at about the same temperature but with an absorbed energy of only 68 J (50 ft-lb). The transition temperature, or the temperature at which the fracture appearance of the specimen contains 50% ductile fracture and 50% cleavage fracture, was estimated to be about -12 C (+10 F) for the L-T specimens and about -7 C (+20 F) for the T-L specimens.

The CVN impact test results for the normalized and stress relieved steel are shown in Tables 8 and 9, and plotted in Figure 11. The CVN results show that stress relieving had a dramatic effect on impact specimens tested in the L-T orientation. There was a slight increase in the normalized and stress relieved CVN results compared with the normalized steel for specimens tested in the T-L

orientation. At -51 C (-60 F), the average CVN impact value for the L-T test specimens was about 94 J (69 ft-lb) as compared with 24 J (18 ft-lb) for the T-L orientation. The upper shelf energy for the L-T oriented specimens started at about 10 C (50 F) and was about 203 J (150 ft-lb). The transition temperature for the L-T specimens was found to be about -12 C (+10 F). For the specimens tested in the T-L orientation, the transition temperature was about -1 C (+25 F).

Lateral Expansion

The lateral expansion (LE) results for the normalized steel are shown in Tables 6 and 7 and plotted in Figure 12. The specimens tested from the L-T orientation possessed better LE values overall. At low test temperatures, LE vales of 1 mm (0.040 inch) or better were measured. For specimens tested at similar temperatures but in the T-L orientation, LE values of 0.5 mm (.020 inch) were measured.

The LE results for the normalized and stress relieved steel are shown in Tables 8 and 9 and plotted in Figure 13. At low test temperatures, stress relieving produced an improvement in the LE values for the specimens tested from the L-T orientation. LE values of 1.4 mm (0.055 inch) and greater were measured for these specimens. Stress relieving did not appear to improve the LE for specimens tested from the T-L orientation.

FRACTURE TOUGHNESS RESULTS

Nil-Ductility Transition

The nil-ductility transition temperature (NDT) was determined for the steel in both the normalized, and normalized and stress relieved conditions. The NDT for both the normalized, and normalized and stress relieved material was found to be the same, -40 C (-40 F).

J-Integral

Data have been presented showing both the mechanical properties and the impact resistance of AAR TC128 steel in both the normalized, and normalized and stress relieved conditions as a function of test temperature. In the fracture analysis of steels, it often behooves the investigator to determine the ability of the steel plate to resist crack initiation and subsequent growth. This ability to resist crack initiation can be shown by the J-integral test. The J test uses a compact tension specimen with an initial crack produced by fatiguing. In performing this test, the compact specimen is loaded to a series of predetermined values and then unloaded from each of these loads. The energy required to extend the crack at each of these loads is ascertained and a corresponding J determined. The specimen is then reloaded to subsequent crack extensions and the J again calculated. In this test, one of the ASTM requisites is that stable crack growth occur, that is, extend under repetitive loading and not grow in an unstable or catastrophic manner.

J-integral tests were conducted on the steel in both the normalized, and normalized and stress relieved conditions. The results, from -51 C (-60 F) to

-18 C (0 F) are shown Tables 10, 11, 12, and 13 and plotted in Figure 14. The figure clearly shows that the normalized and stress relieved steel, for either the L-T or T-L orientations, was more resistant to crack initiation than the normalized steel. Shown in the figure beneath the upper two curves is the letter "S". This letter indicates that the crack growth for the steel at these test temperatures was stable. Examination of these specimens after removal from the test apparatus revealed that a crack did not propagate beyond the initial fatigue crack, and the region immediately in front of the fatigue crack was severely blunted. A high J value was obtained for these specimens. As for the normalized material, only at a temperature of -18 C (0 F) was there stable fracture. At other test temperatures, even though a J value was obtained, unstable fractures occurred.

Crack Tip Opening Displacement

CTOD tests were performed on the normalized, and normalized and stress relieved steels at -51 C (-60 F). The results are shown in Table 14. Since no stable crack growth was obtained, only crack blunting and then plastic collapse, testing at higher temperatures was unwarranted.

According to the ASTM Method E 1221-88, if stable crack growth does not occur, the plastic displacement at the maximum load, δ_m, should be taken as the CTOD, and used to determine the corresponding J's and K's. (See Table 14 for the equations used.) The CTOD test results, and the corresponding fracture toughness values, clearly show that the normalized and stress relieved material was more resistant to crack initiation than the normalized material.

Crack Arrest

Having determined both materials' resistance to initiate a crack, the ability to stop a propagating crack was determined. The results for the normalized, and normalized and stress relieved AAR TC128 grade B steel are shown in Tables 15, 16, 17, and 18, and graphically in Figure 15. It is important to note that the crack arrest value, denoted as K_a, is a material property like the UTS, YS, etc. As expected, the crack arrest value increased as the test temperature increased. Both the normalized, and normalized and stress relieved materials have crack arrest values that are characteristic of other ferrite/pearlite steels.

DISCUSSION AND CONCLUSIONS

A database has been developed for normalized, and normalized and stress relieved AAR TC128 grade B steel. The mechanical properties, in terms of the ultimate and yield strengths, reduction in area, and elongation showed the steel to possess properties that are not uncommon for this steel. Impact tests performed in both conditions showed that the normalized and stress relieved material had better impact properties at low temperatures than the normalized material. The impact results also showed that the normalized and stress relieved material had a higher upper-shelf value than the normalized material. In essence the mechanical properties, i.e., UTS, YS etc., and impact properties over the temperatures tested revealed that the normalized and stress relieved material was better than the normalized material.

The test results are those that are commonly reported for these steels, and are identified as the basic test results needed. Often in accidents involving tank cars that are made of these materials, it is important that the investigator know the ability of this material to resist crack initiation, for example when it is impacted by a knuckle coupler from another tank car, and also the ability of the same material to arrest a propagating crack. These two properties were determined for the steels in both the normalized, and normalized conditions. Low temperature, -51 C(-60 F), test results indicated that the normalized and stress relieved material was more resistant to crack initiation than the normalized material. The crack arrest property, over the test temperature range was comparable and similar to that observed for other ferrite/pearlite steels. Of primary importance was the difference between the crack initiation values and the arrest values for these conditions. It was found that the difference in these values was greater for the normalized and stress relieved material than for the normalized material. This indicates that under impact conditions, where no fire is involved, the normalized and stress relieved material would be more resistant to crack initiation that the normalized material.

In conclusion, the test results, in particular the fracture toughness results, clearly indicate that the normalized and stress relieved material was better than the normalized material.

ACKNOWLEDGEMENT

This work was supported by the Federal Railroad Administration and monitored by Ms. Claire Orth, Chief of the Safety Research Division.

Table 1. Chemical Composition (Wt%), the AAR TC128 Grade B Specification, and Heat Analyses on Plate "I".

	AAR[1] Specification	Heat[2] Analyses	Check[3] Analyses (1)	Check[3] Analyses (2)
Carbon	0.25 max	0.22	0.21	0.21
Manganese	1.0 - 1.5	1.27	1.13	1.11
Phosphorus	0.035 max	0.015	0.012	0.010
Sulphur	0.040 max	0.012	0.010	0.008
Silicon	0.05 - 0.50	0.241	0.22	0.21
Nickel	0.25 max	0.04	0.03	0.03
Chromium	0.25 max	0.23	0.25	0.24
Molybdenum	0.08 max	0.062	0.06	0.06
Copper	0.035 max	0.034	0.03	0.03
Aluminum	NR[4]	0.065	0.063	0.063
Niobium	NR	NR	<0.005	<0.005
Vanadium	0.08 max	0.034	0.029	0.028
Nitrogen	NR	NR	0.0065	0.0061
Calcium	NR	NR	<0.001	<0.001
C.E.[5]	0.62 max	0.50	0.47	0.46

1 AAR Specifications for Tank Cars: Specification M-1002, M128.
2 Bethlehem Steel Corporation.
3 NIST.
4 Not Required
5 C.E. = Carbon Equivalent = C + Mn/6 + (Cr + Mo + V)/5 + (Cu + Ni)/15.

Table 2. Tensile Test Results for Normalized AAR TC128 Grade B Steel. Specimens Were Tested in the ASTM L-T Orientation.

Specimen Number	Test Temp. C	(F)	UTS MPa	(ksi)	0.2% YS MPa	(ksi)	RA %	Elong. (25 mm),%
T11	22	72	673.2	97.7	446.5	64.8	65.5	28.5
T12	22	72	675.9	98.1	456.1	66.2	64.3	27.8
T3	-18	0	716.6	104.0	474.0	68.6	58.6	27.1
T4	-18	0	717.2	104.1	467.8	67.9	66.8	29.1
T5	-29	-20	711.0	103.2	474.7	68.9	64.9	30.7
T6	-29	-20	720.0	104.5	485.1	70.4	61.8	28.6
T7	-40	-40	727.6	105.6	488.5	70.9	63.6	29.1
T8	-40	-40	729.0	105.8	490.6	71.2	63.2	31.0
T9	-50	-60	746.9	108.4	497.5	72.2	64.0	29.2
T10	-51	-60	726.9	105.5	480.2	69.7	65.8	29.3

Table 3. Tensile Test Results for Normalized AAR TC128 Grade B Steel. Specimens Were Tested in the ASTM T-L Orientation.

Specimen	Test Temp.		UTS		0.2% YS		RA	Elong.
Number	C	(F)	MPa	(ksi)	MPa	(ksi)	%	(25 mm),%
T43	22	72	607.7	88.2	408.6	59.3	60.9	32.0
T44	22	72	606.3	88.0	406.5	59.0	61.2	32.6
T35	-18	0	644.9	93.6	401.0	58.2	63.0	30.0
T36	-18	0	647.0	93.9	389.3	56.5	61.7	27.3
T37	-29	-20	654.6	95.0	443.7	64.4	60.0	30.5
T38	-29	-20	656.6	95.3	443.0	64.3	62.1	30.9
T39	-40	-40	668.3	97.0	442.3	64.2	60.9	32.2
T40	-40	-40	667.6	96.9	445.1	64.6	56.3	32.2
T41	-51	-60	677.3	98.3	462.3	67.1	57.7	33.3
T42	-51	-60	680.7	98.8	459.6	66.7	62.2	33.7

Table 4. Tensile Test Results for Normalized and Stress Relieved AAR TC128 Grade B Steel. Specimens Were Tested in the ASTM L-T Orientation.

Specimen Number	Test Temp. C	(F)	UTS MPa	(ksi)	0.2% YS MPa	(ksi)	RA %	Elong. (25 mm),%
T27	22	72	618.7	89.8	427.9	62.1	69.6	32.5
T28	22	72	619.4	89.9	429.9	62.4	68.0	31.4
T19	-18	0	660.8	95.9	465.1	67.5	67.5	30.9
T20	-18	0	658.7	95.6	474.0	68.8	67.9	30.6
T21	-29	-20	671.1	97.4	480.2	69.7	68.4	31.0
T22	-29	-20	662.8	96.2	472.7	68.6	68.5	30.7
T23	-40	-40	676.6	98.2	474.0	68.8	65.9	31.6
T24	-40	-40	674.5	97.9	480.2	69.7	68.2	31.8
T25	-51	-60	693.1	100.6	509.2	73.9	67.6	32.1
T26	-51	-60	691.6	100.4	491.9	71.4	67.0	32.7

Table 5. Tensile Test Results for Normalized and Stress Relieved AAR TC128 Grade B Steel. Specimens Were Tested in the ASTM T-L Orientation

Specimen	Test Temp.		UTS		0.2% YS		RA	Elong.
Number	C	(F)	MPa	(ksi)	MPa	(ksi)	%	(25 mm),%
T59	22	72	556.7	80.8	394.1	57.2	65.0	33.7
T60	22	72	557.4	80.9	395.5	57.4	62.4	32.8
T51	-18	0	593.2	86.1	413.4	60.0	56.6	31.9
T52	-18	0	593.2	86.1	407.2	59.1	62.0	33.6
T53	-29	-20	600.1	87.1	416.2	60.4	58.1	33.7
T54	-29	-20	601.5	87.3	418.2	60.7	63.3	34.6
T55	-40	-40	612.5	88.9	448.5	65.1	64.4	35.3
T56	-40	-40	616.7	89.5	434.1	63.0	60.6	33.4
T57	-51	-60	624.9	90.7	444.4	64.5	61.6	34.2
T58	-51	-60	627.7	91.1	453.4	65.8	62.0	35.0

Table 6. Impact Test Results for Normalized AAR TC128 Grade B Steel. Specimens Were Tested in the ASTM L-T Orientation.

Specimen Number	Test Temp. C	(F)	Energy Absorbed J	(Ft-lb)	Lateral Expansion mm	(inch)
I1	-50	-58	59.7	44.0	0.86	34.0
I2	-50	-58	94.9	70.0	1.40	55.0
I3	-50	-58	75.9	56.0	1.12	44.0
I7	-46	-50	77.3	57.0	1.12	44.0
I8	-46	-50	73.2	54.0	1.09	43.0
I9	-46	-50	78.6	58.0	1.18	46.5
I12	-31	-25	50.2	37.0	0.77	30.5
I13	-31	-25	88.1	65.0	1.35	53.0
I14	-31	-25	50.2	37.0	1.19	47.0
I15	-30	-25	81.3	60.0	0.81	32.0
I22	-23	-10	50.2	37.0	0.77	30.5
I23	-23	-10	100.3	74.0	1.50	59.0
I24	-23	-10	63.7	47.0	0.94	37.0
I10	-18	0	119.3	88.0	1.65	65.0
I11	-18	0	127.4	94.0	1.79	70.5
I25	-9	+15	80.0	59.0	1.02	40.0
I26	-9	+15	168.1	124.0	2.21	87.0
I16	-1	+30	162.7	120.0	2.29	90.0
I17	-1	+30	145.1	107.0	2.13	84.0
I18	+10	+50	149.1	110.0	2.01	79.0
I19	+10	+50	161.3	119.0	2.26	89.0
I4	+22	+73	185.7	137.0	2.30	90.5
I5	+22	+73	188.4	139.0	2.32	91.5
I6	+22	+73	189.8	140.0	2.34	92.0
I20	+38	+100	185.7	137.0	2.27	89.5
I21	+38	+100	165.4	122.0	2.21	87.0
I27	+93	+200	154.6	114.0	2.11	83.0
I28	*93	+200	165.4	122.0	2.12	83.5

Table 7. Impact Test Results for Normalized AAR TC128 Grade B Steel. Specimens Were Tested in the ASTM T-L Orientation.

Specimen Number	Test Temp. C	(F)	Energy Absorbed J	(Ft-lb)	Lateral Expansion mm	(inch)
I61	-50	-58	29.2	21.1	0.51	20.0
I62	-50	-58	29.8	22.0	0.46	18.0
I63	-50	-58	29.8	22.0	0.43	17.0
I67	-46	-50	31.9	23.5	0.53	21.0
I68	-46	-50	44.1	32.5	0.69	27.0
I69	-46	-50	35.9	26.5	0.57	22.5
I72	-31	-25	36.6	27.0	0.69	27.0
I73	-30	-25	47.5	35.0	0.84	33.0
I80	-23	-10	43.4	32.0	0.79	31.0
I81	-23	-10	50.2	37.0	0.86	34.0
I70	-18	0	59.7	44.0	1.07	42.0
I71	-18	0	51.5	38.0	0.88	34.5
I82	-9	+15	67.8	50.0	1.19	47.0
I83	-9	+15	47.5	35.0	0.93	36.5
I74	-1	+30	66.4	49.0	1.18	46.5
I75	-1	+30	65.1	48.0	1.21	47.5
I76	+10	+50	80.0	59.0	1.41	55.5
I77	+10	+50	80.0	59.0	1.45	57.0
I64	+22	+73	81.3	60.0	1.41	55.5
I65	+22	+73	86.8	64.0	1.46	57.5
I66	+22	+73	86.8	64.0	1.50	59.0
I78	+38	+100	78.6	58.0	1.40	55.0
I79	+38	+100	81.3	60.0	1.45	57.0
I84	+93	+200	78.6	58.0	1.47	58.0
I85	+93	+200	80.0	59.0	1.48	58.5

Table 8. Impact Test Results for Normalized and Stress Relieved AAR TC128 Grade B Steel. Specimens Were Tested in the ASTM L-T Orientation.

Specimen Number	Test Temp. C	(F)	Energy Absorbed J	(Ft-lb)	Lateral Expansion mm	(inch)
I37	-51	-60	67.8	50.0	1.07	42.0
I38	-51	-60	62.4	46.0	0.94	37.0
I39	-51	-60	151.9	112.0	2.01	79.0
I34	-46	-50	74.6	55.0	0.99	39.0
I35	-46	-50	119.3	88.0	1.63	64.0
I36	-46	-50	108.5	80.0	1.49	58.5
I40	-31	-25	115.2	85.0	1.47	58.0
I41	-31	-25	103.0	76.0	1.36	53.5
I42	-23	-10	139.6	103.0	0.90	35.3
I43	-23	-10	169.5	125.0	1.06	41.8
I44	-18	0	155.9	115.0	1.97	77.5
I45	-18	0	123.4	91.0	1.65	65.0
I46	-9	+15	142.4	105.0	1.92	75.5
I47	-9	+15	122.0	90.0	1.77	69.5
I48	-1	+30	181.7	134.0	2.11	83.0
I49	-1	+30	179.0	132.0	2.13	84.0
I50	+10	+50	183.0	135.0	2.24	88.0
I51	+10	+50	173.5	128.0	2.20	86.5
I31	+20	+68	218.3	161.0	2.35	92.5
I32	+20	+68	223.7	165.0	2.31	91.0
I33	+20	+68	233.2	172.0	2.34	92.0
I52	+42	+107	176.3	130.0	2.16	85.0
I53	+47	+107	183.0	135.0	2.16	85.0
I54	+93	+200	179.0	132.0	22.0	86.5
I55	+93	+200	181.7	134.0	2.18	86.0

Table 9. Impact Test Results for Normalized and Stress Relieved AAR TC128 Grade B Steel. Specimens Were Tested in the ASTM T-L Orientation.

Specimen Number	Test Temp. C	(F)	Energy Absorbed J	(Ft-lb)	Lateral Expansion mm	(inch)
I97	-51	-60	25.1	18.5	0.42	16.5
I98	-51	-60	21.0	15.5	0.36	14.0
I99	-51	-60	25.8	19.0	0.36	14.0
I94	-46	-50	24.4	18.0	0.47	18.5
I95	-46	-50	25.8	19.0	0.44	17.5
I96	-46	-50	24.4	18.0	0.39	15.5
I100	-31	-25	51.5	38.0	0.84	33.0
I101	-31	-25	42.0	31.0	0.71	28.0
I102	-23	-10	44.7	33.0	0.77	30.0
I103	-23	-10	42.0	31.0	0.67	26.5
I104	-18	0	59.7	44.0	1.00	39.5
I105	-18	0	44.7	33.0	0.76	30.0
I106	-9	+15	61.0	45.0	0.72	28.5
I107	-9	+15	77.3	57.0	1.02	40.0
I108	-1	+30	77.3	57.0	1.24	49.0
I109	-1	+30	67.8	50.0	1.22	48.0
I110	+10	+50	77.3	57.0	1.30	51.0
I111	+10	+50	75.9	56.0	1.30	51.0
I91	+20	+68	100.3	74.0	1.35	53.0
I92	+20	+68	105.8	78.0	1.59	62.5
I93	+20	+68	101.7	75.0	1.52	60.0
I112	+42	+107	88.1	65.0	1.51	59.5
I113	+42	+107	88.1	65.0	1.45	57.0
I114	+93	+200	92.2	68.0	1.59	62.5
I115	+93	+200	90.8	67.0	1.52	60.0

Table 10. J-Integral Test Results (Crack Initiation K's) for Normalized AAR TC128 Grade B Steel Tested in the ASTM L-T Orientation.

Specimen Number	Test Temp.		J		K^1		Average[2]	Type of Fracture	
	C	(F)	kJ/m^2	$(in\text{-}lbf/in^2)$	$MPa \cdot m^{1/2}$	$(ksi \cdot in^{1/2})$	(SI)	Stable	Unstable
CT25	-51	-60	105	600	145	132	--		*
CT26	-51	-60	21	122	66	60	106		*
CT27	-40	-40	38	218	87	79	--		*
CT28	-40	-40	119	682	154	140	120		*
CT29	-29	-20	67	382	116	105	116		*
CT30	-18	0	262	1500	229	208	229	*	

1 Plane Stress: $K^2 = JE$.
2 Average at test temperatures in SI units.

Table 11. J-Integral Test Results (Crack Initiation K's) for Normalized AAR TC128 Grade B Steel Tested in the ASTM T-L Orientation.

Specimen Number	Test Temp. C	(F)	J kJ/m^2	$(in\text{-}lbf/in^2)$	K[1] $MPa\cdot m^{1/2}$	$(ksi\cdot in^{1/2})$	Average[2] (SI)	Type of Fracture Stable	Unstable
CT2	-51	-60	29	167	77	70	--		*
CT3	-51	-60	64	307	113	103	95		*
CT4	-40	-40	34	194	83	75	--		*
CT5	-40	-40	50	288	100	91	92		*
CT6	-29	-20	36	207	85	77	--		*
CT7	-18	0	123	700	156	142	120	*	

1 Plane Stress: $K^2 = JE$.
2 Average at test temperatures in SI units.

Table 12. J-Integral Test Results (Crack Initiation K's) for Normalized and Stress Relieved AAR TC128 Grade B Steel Tested in the ASTM L-T Orientation.

Specimen Number	Test Temp. C	Test Temp. (F)	J kJ/m^2	J $(in\text{-}lbf/in^2)$	K[1] $MPa \cdot m^{1/2}$	K[1] $(ksi \cdot in^{1/2})$	Average[2] (SI)	Type of Fracture Stable[3]	Type of Fracture Unstable
CT37	-51	-60	525	3000	324	295	--	*	
CT38	-51	-60	44	251	94	85	--		*
CT39	-51	-60	350	2000	264	240	227	*	
CT40	-40	-40	479	2738	310	282	--	*	
CT41	-40	-40	667	3807	365	332	323	*	

1 Plane Stress: $K^2 = JE$.
2 Average at test temperatures in SI units.
3 Stable crack growth, then crack blunting.

Table 13. J-Integral Test Results (Crack Initiation K's) for Normalized and Stress Relieved AAR TC128 Grade B Steel Tested in the ASTM T-L Orientation.

Specimen	Test Temp.		J		K[1]		Average[2]	Type of Fracture	
Number	C	(F)	kJ/m^2	$(in\text{-}lbf/in^2)$	$MPa \cdot m^{1/2}$	$(ksi \cdot in^{1/2})$	(SI)	Stable[3]	Unstable
CT13	-51	-60	83	474	129	117	--	*	
CT14	-51	-60	158	900	178	162	154	*	
CT15	-40	-40	123	700	157	143	--	*	
CT17	-40	-40	153	876	175	159	166	*	

1 Plane Stress: $K^2 = JE$.
2 Average at test temperatures in SI units.
3 Stable crack growth, then crack blunting.

Table 14. CTOD Test Results for Normalized, and Normalized and Stress Relieved AAR TC 128 Grade B Steel Tested at -51 C (-60 F)

Specimen Number	δ_m		Plane Stress[1] J		Plane Strain[2] J		Plane Stress[3] K		Plane Strain[4] K	
	$x10^{-5}$ m	$x10^{-3}$ in	kJ/m^2	$(in\text{-}lbf/in^2)$	kJ/m^2	$(in\text{-}lbf/in^2)$	$MPa \cdot m^{1/2}$	$(ksi \cdot in^{1/2})$	$MPa \cdot m^{1/2}$	$(ksi \cdot in^{1/2})$
OD6[5]	22.2	8.7	165	943	220	1257	182	165	210	191
OD7[5]	26.2	10.3	195	1116	260	1488	198	180	229	208
OD8[5]	31.2	12.3	233	1333	311	1778	217	197	250	227
OD27[6]	34.0	13.4	253	1447	338	1930	226	205	261	237
OD28[6]	37.1	14.6	275	1574	367	2099	235	214	272	247
OD29[6]	36.8	14.5	274	1567	366	2089	234	213	271	246

1 J = (1.2 * flow * δ_m): where δ_m = displacement at max. load.
2 J = (1.6 * flow * δ_m): where δ_m = displacement at max. load.
3 K = (1.2 * E * flow stress * δ_m): where δ_m = displacement at max. load, where E = modulus of elasticity.
4 K = (1.6 * E * flow stress * δ_m): where δ_m = displacement at max. load.
5 Normalized.
6 Normalized and stress relieved.

Table 15. Crack Arrest Test Results (K_a) for Normalized and Stress Relieved AAR TC128 Grade B Steel Tested in the ASTM L-T Orientation

Specimen Number	Test Temp. C	(F)	K_a $MPa \cdot m^{1/2}$	($ksi \cdot in^{1/2}$)
I-21	-51	-60	48	44
I-22	-51	-60	61	55
I-23	-51	-60	56	51
I-24	-29	-20	64	58
I-25	-29	-20	64	58
I-26	-29	-20	72	65
I-27	-18	0	CRACK DID NOT RUN	
I-28	-18	0	83	75
I-29	-18	0	66	60
I-30	-18	0	INSUF. CRACK GROWTH	
I-31	-40	-40	48	44
I-32	-40	-40	46	42
I-33	-40	-40	65	59

Table 16. Crack Arrest Test Results (K_a) for Normalized and Stress Relieved AAR TC128 Grade B Steel Tested in the ASTM T-L Orientation

Specimen Number	Test Temp.		K_a	
	C	(F)	$MPa \cdot m^{1/2}$	($ksi \cdot in^{1/2}$)
I-37	-51	-60	42	38
I-38	-51	-60	54	49
I-39	-51	-60	63	57
I-40	-29	-20	79	72
I-41	-29	-20	68	62
I-43	-18	0	63	57
I-44	-18	0	73	66
I-45	-18	0	72	65
I-46	-40	-40	57	52
I-47	-40	-40	59	54
I-48	-40	-40	63	57
I-49	-29	-20	66	60

Table 17. Crack Arrest Test Results (K_a) for Normalized and Stress Relieved AAR TC128 Grade B Steel Tested in the ASTM L-T Orientation

Specimen Number	Test Temp. C	(F)	K_a $MPa \cdot m^{1/2}$	$(ksi \cdot in^{1/2})$
I-1	-51	-60	46	42
I-2	-51	-60	57	52
I-3	-51	-60	57	52
I-4	-52	-60	61	55
I-6	-29	-20	62	56
I-7	-29	-20	67	61
I-8	-29	-20	67	61
I-9	-18	0	CRACK DID NOT RUN	
I-10	-18	0	86	78
I-11	-18	0	53	48
I-12	-18	0	86	78
I-13	-18	0	RAN OUT OF SIDE GROOVES	
I-14	-40	-40	56	51
I-15	-40	-40	59	54
I-16	-40	-40	65	59

Table 18. Crack Arrest Test Results (K_a) for Normalized and Stress Relieved AAR TC128 Grade B Steel Tested in the ASTM T-L Orientation

Specimen Number	Test Temp. C	Test Temp. (F)	K_a $MPa \cdot m^{\frac{1}{2}}$	K_a $(ksi \cdot in^{\frac{1}{2}})$
I-55	-51	-60	50	45
I-56	-51	-60	54	49
I-57	-51	-60	65	59
I-58	-29	-20	CRACK TUNNELED (INV.)	
I-59	-29	-20	CRACK TUNNELED (INV.)	
I-60	-29	-20	75	68
I-62	-29	-20	67	61
I-63	-29	-20	72	65
I-64	-18	0	CRACK DID NOT RUN	
I-65	-18	0	CRACK DID NOT RUN	
I-66	-40	-40	47	43
I-67	-40	-40	55	50
I-68	-40	-40	50	45

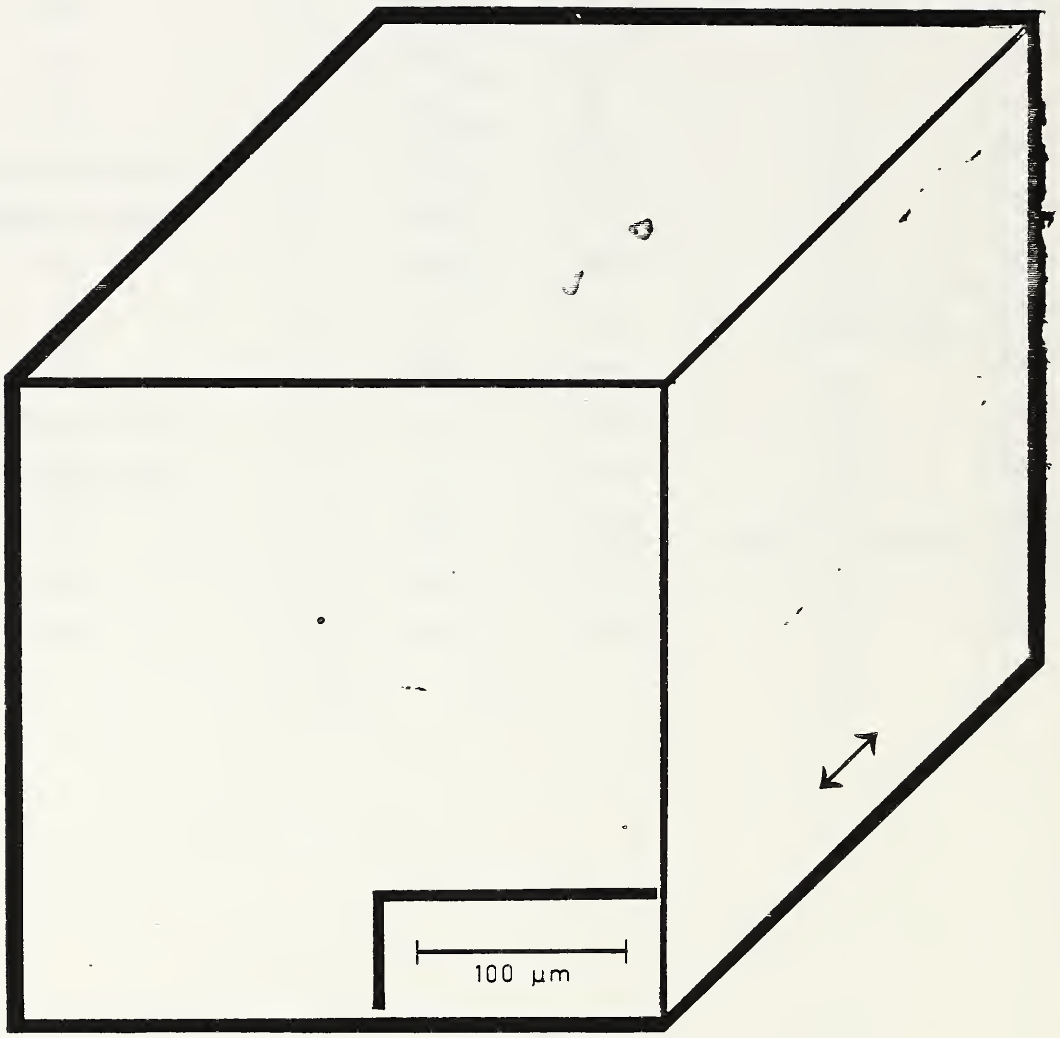


Figure 1. Photomicrographs of as-polished AAR TC128 grade B steel in three orthogonal directions. The inclusions appear to be manganese sulfide. The arrow shows the predominant rolling direction in the plate.

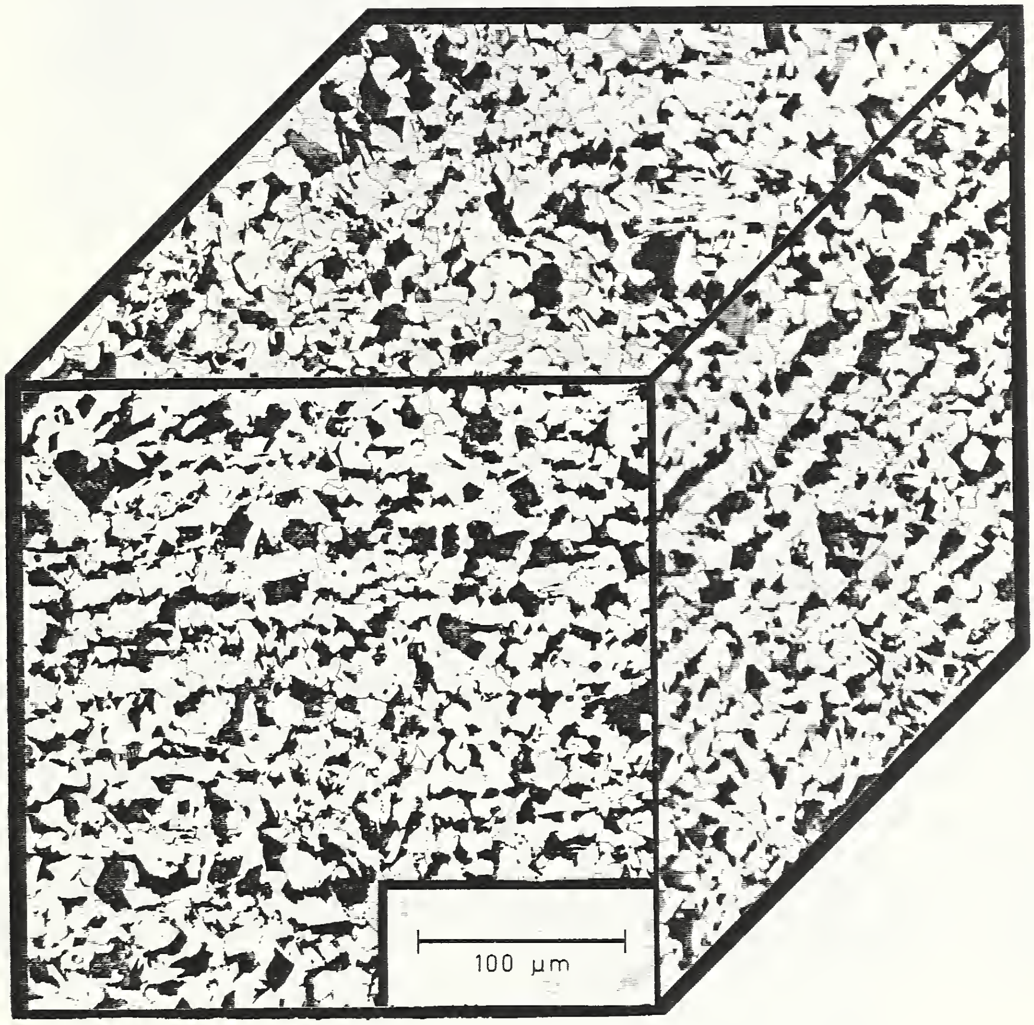
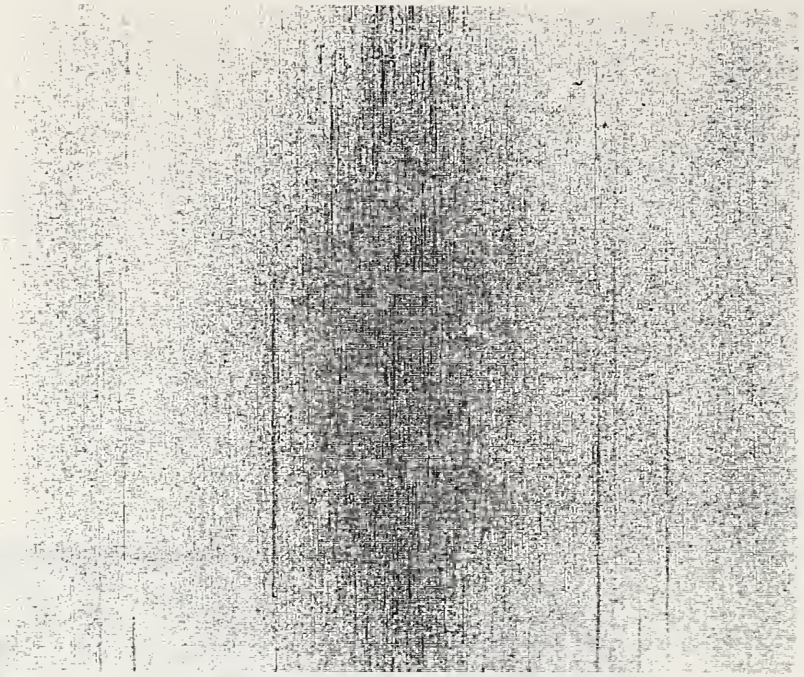
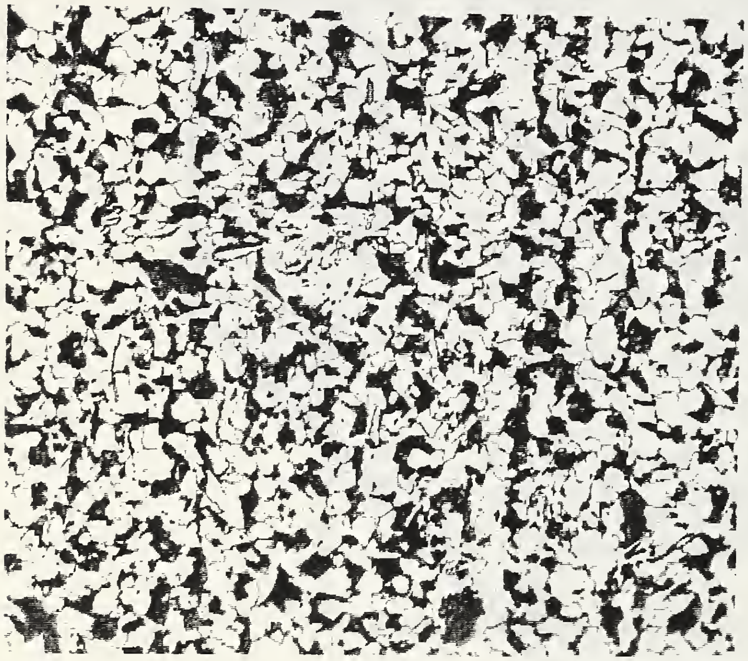


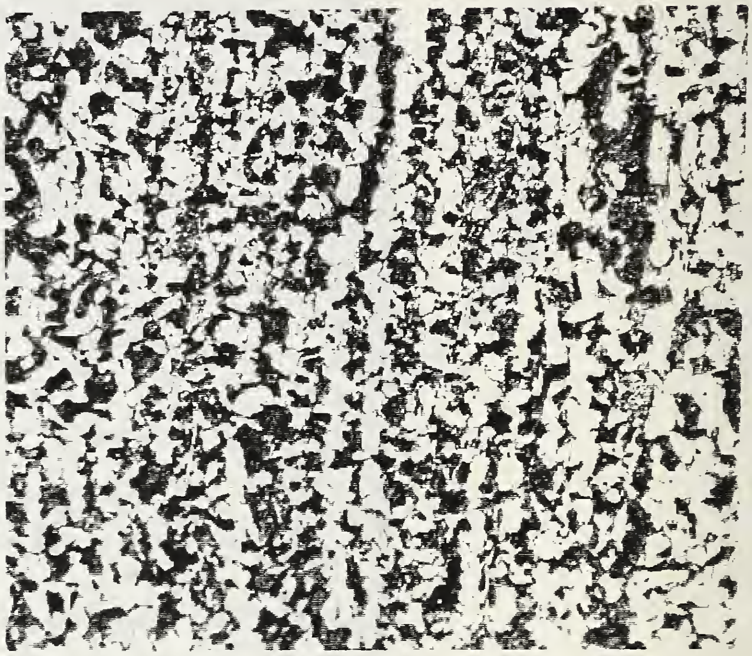
Figure 2. Photomicrographs of etched AAR TC128 grade B steel in three orthogonal directions. The microstructure consists of pearlite (dark) and ferrite (light). The ferrite appears to be uniform in grain size, indicative of normalized material.
Etch: 1% Nital



a

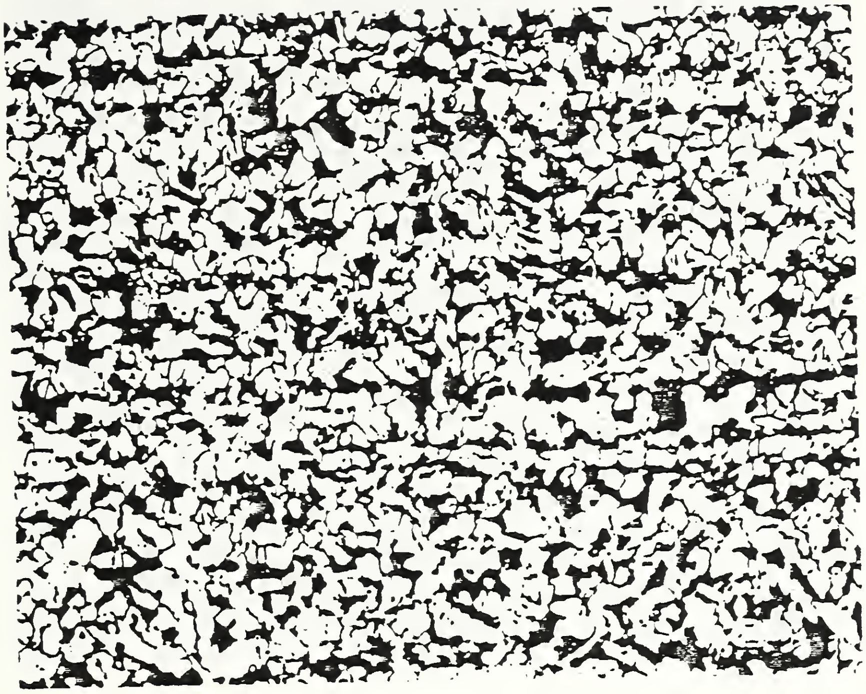


b

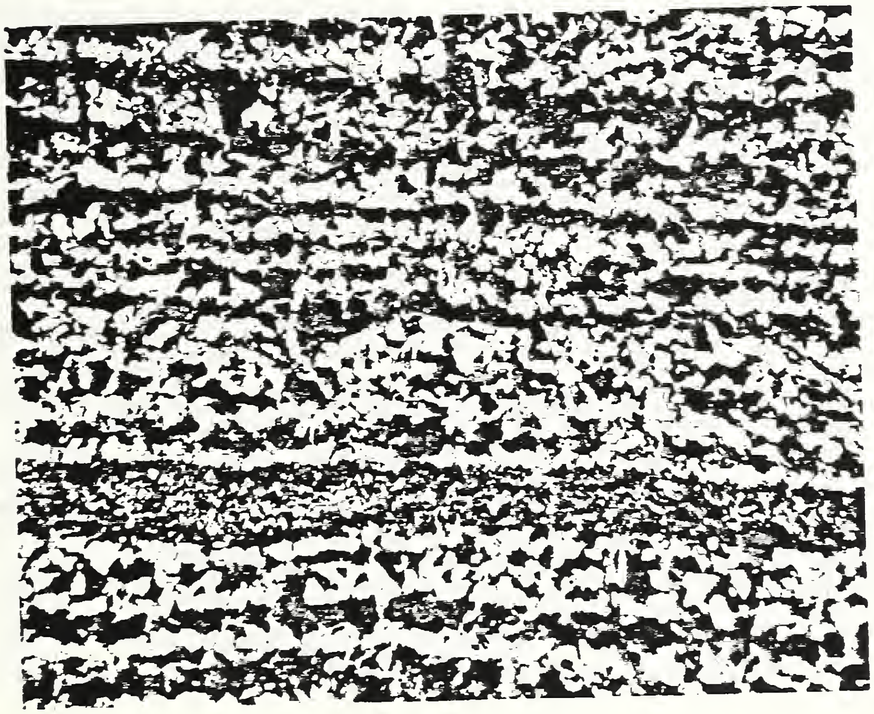


c

Figure 3. Photomicrographs showing the overall microstructure (a), that located at the centerline (b), and quarter-thickness (c), locations. Microstructural banding, i.e., heavy concentration of coarse pearlite, was observed along the center line of the plate. Mag: a) X6.6; b and c) X250. Etch: 2% Nital

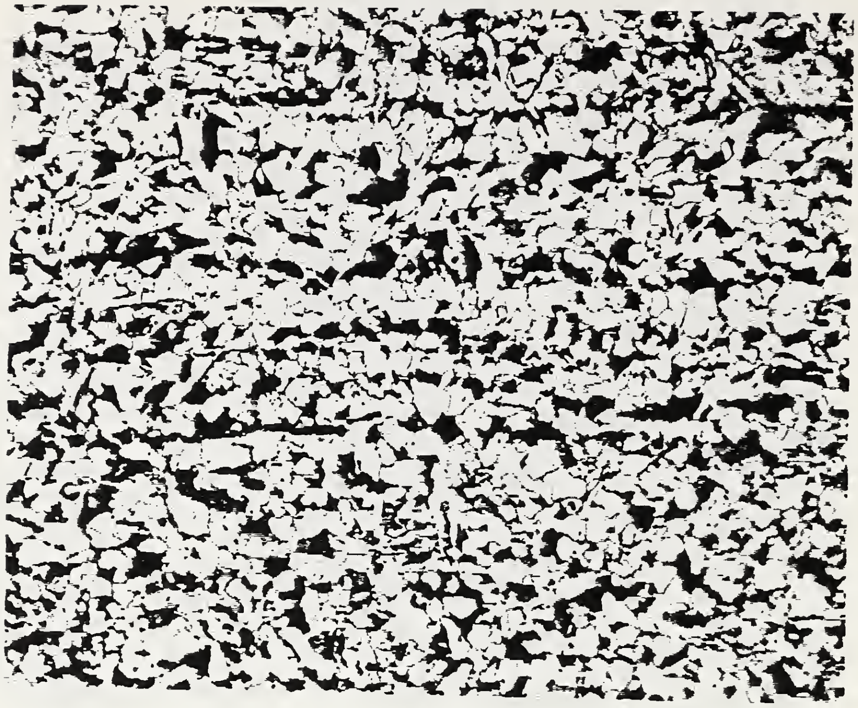


a

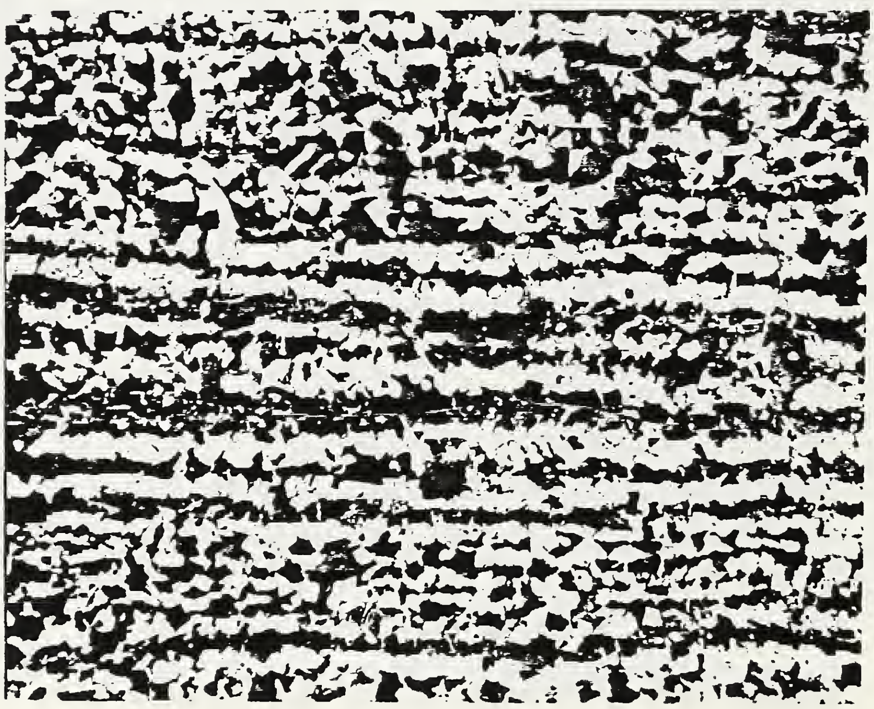


b

Figure 4. Photomicrographs of normalized and stress relieved AAR TC128 grade B steel in the etched condition, in the ASTM T-L orientation. The photomicrographs were taken at the edge (a), and at the quarter thickness locations (b) of the specimen.
Mag: Both X250 Etch: 1% Nital



a



b

Figure 5. Photomicrographs of normalized and stress relieved AAR TC128 grade B steel in the etched condition, in the ASTM L-T orientation. The photomicrographs were taken at the edge (a), and at the quarter-thickness locations (b) of the specimen.
Mag: Both X250 Etch: 1% Nital

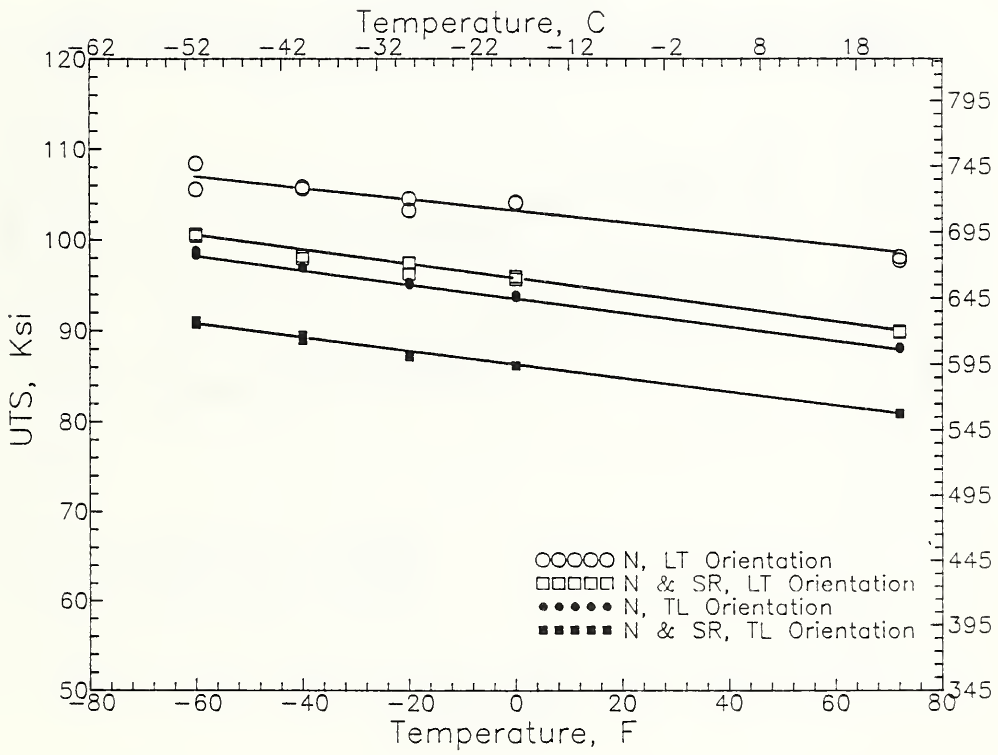


Figure 6. Ultimate tensile strength as a function of test temperature for normalized, and normalized and stress relieved AAR TC128 grade B steel. The ASTM L-T and T-L orientations are compared.

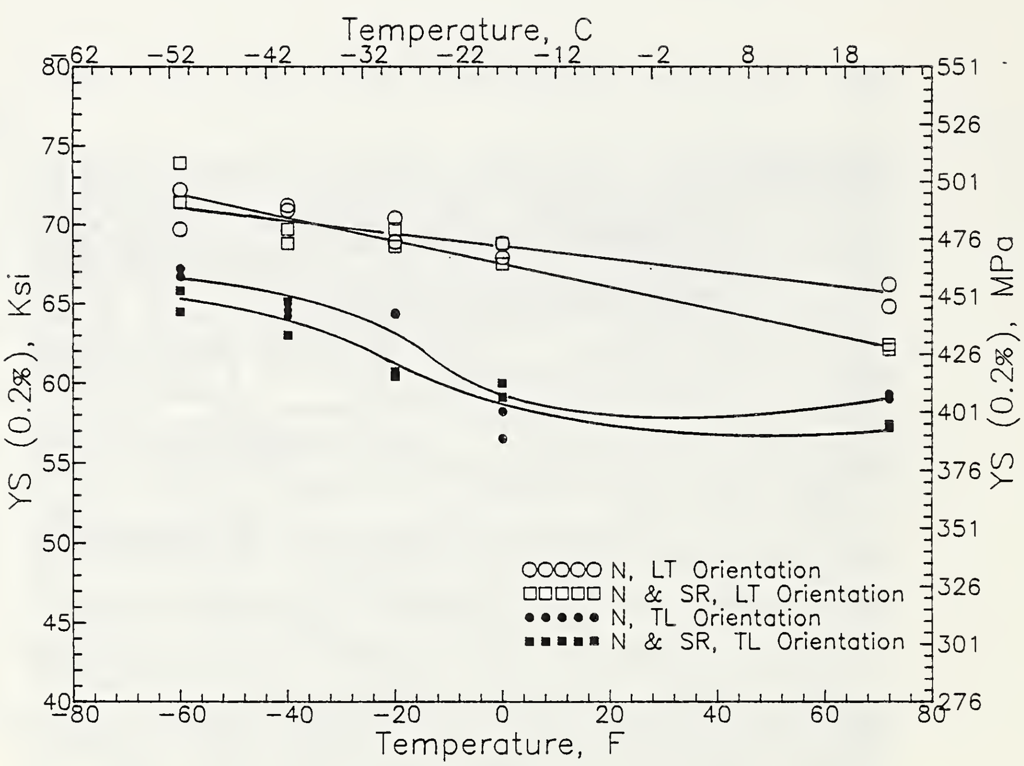


Figure 7. Yield strength, 0.2% offset, as a function of test temperature for normalized, and normalized and stress relieved AAR TC128 grade B steel. The ASTM L-T and T-L orientations are compared.

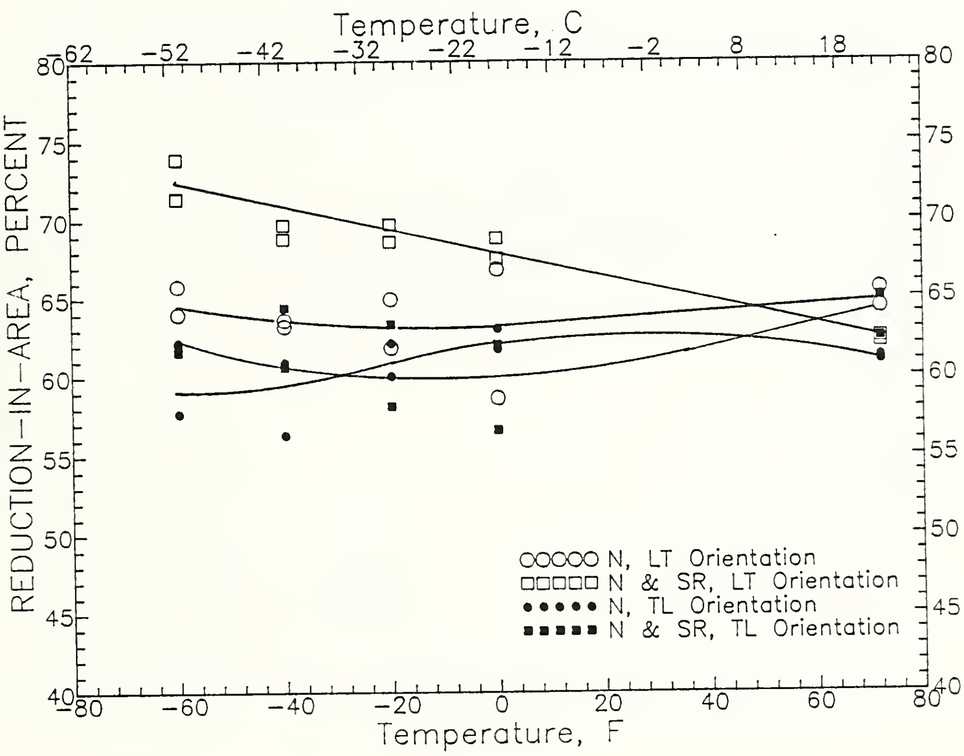


Figure 8. Reduction in area, %, as a function of test temperature for normalized, and normalized and stress relieved AAR TC128 grade B steel. The ASTM L-T and T-L orientations are compared.

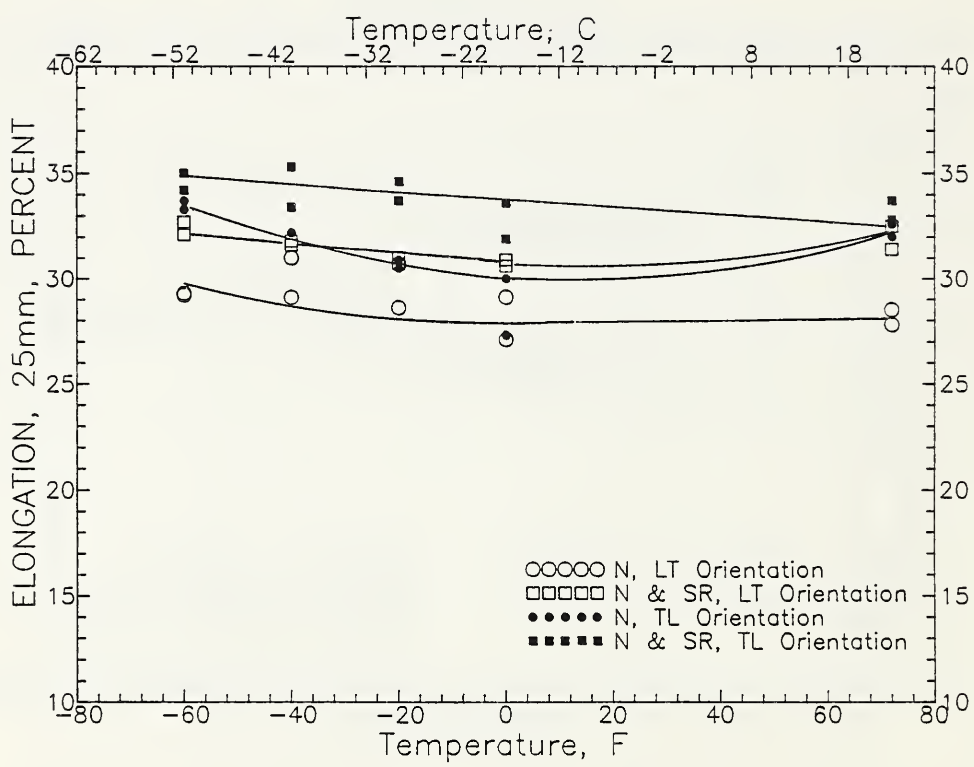


Figure 9. Elongation in 25 mm (1 inch), %, as a function of test temperature for normalized, and normalized and stress relieved AAR TC128 grade B steel. The ASTM L-T and T-L orientations are compared.

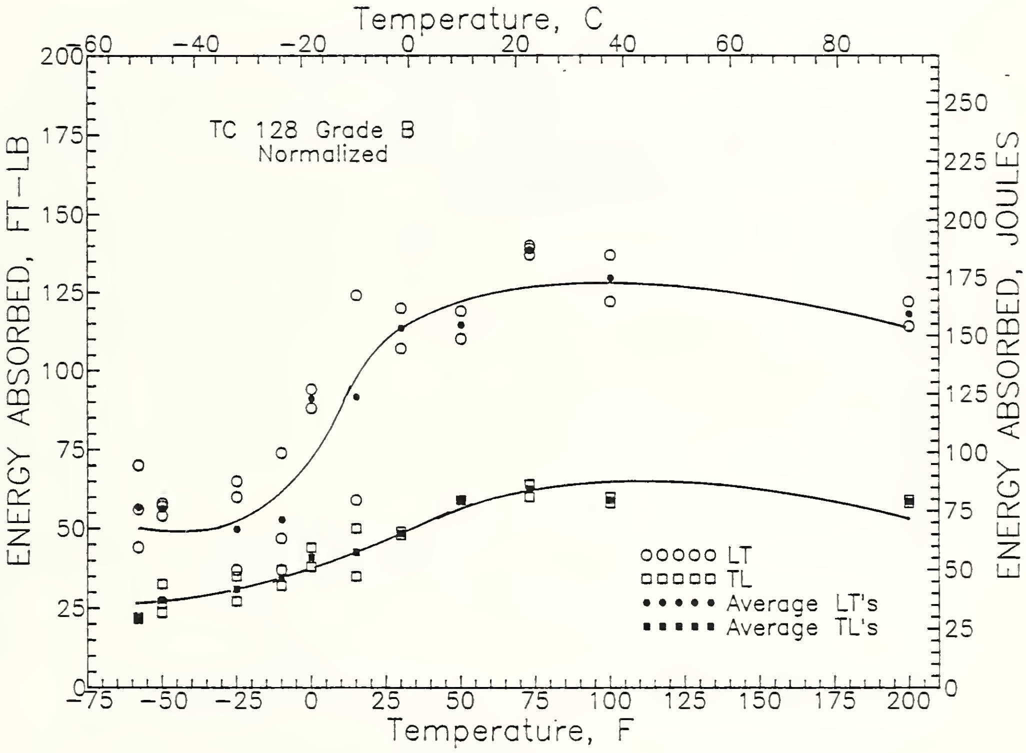


Figure 10. Charpy V-notch impact results for normalized AAR TC128 grade B steel. The ASTM L-T and T-L orientations are compared.

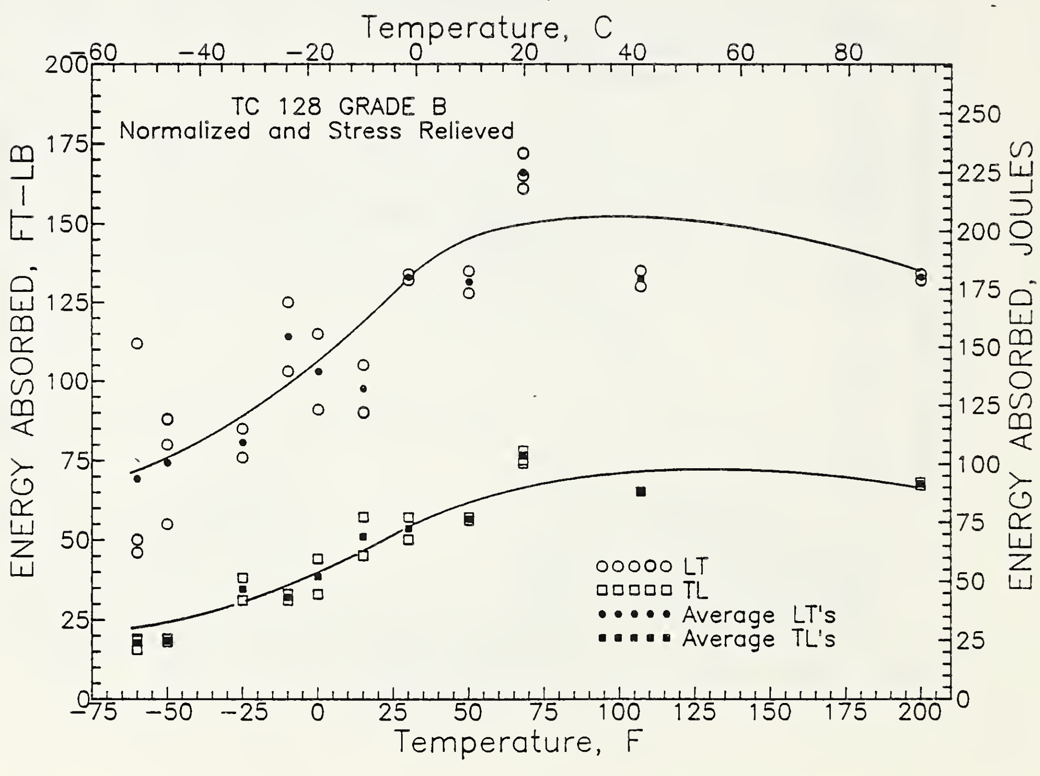


Figure 11. Charpy V-notch impact results for normalized and stress relieved AAR TC128 grade B steel. The ASTM L-T and T-L orientations are compared.

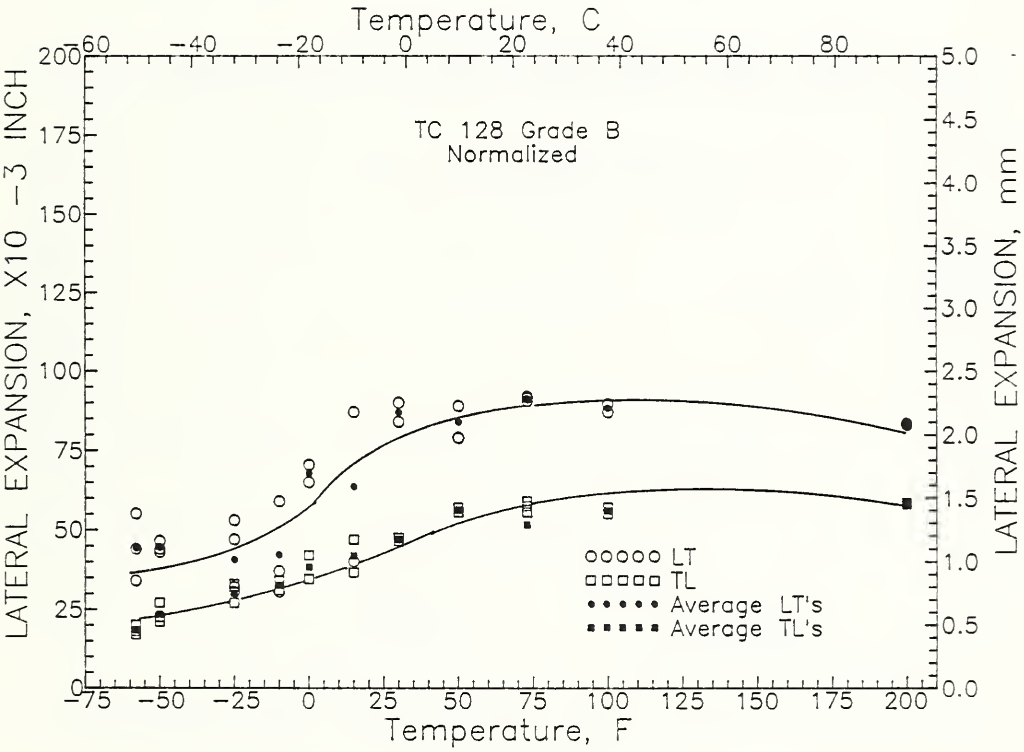


Figure 12. Lateral expansion results for normalized AAR TC128 grade B steel. The ASTM L-T and T-L orientations are compared.

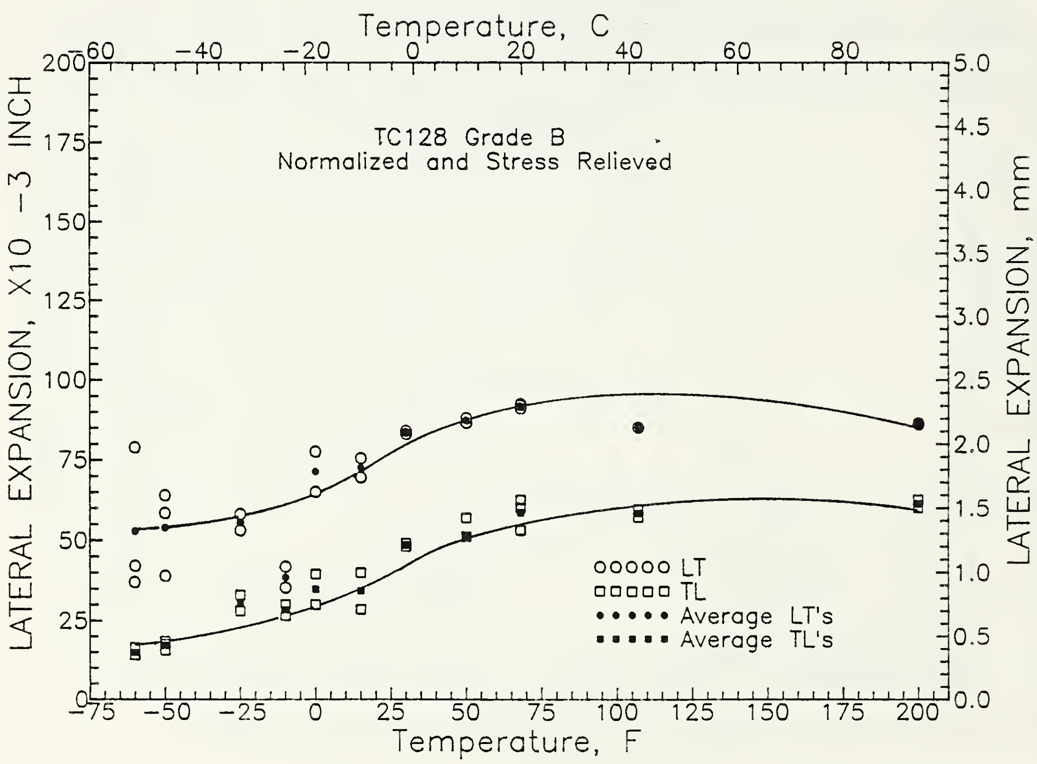


Figure 13. Lateral expansion results for normalized and stress relieved AAR TC128 grade B steel. The ASTM L-T and T-L orientations are compared.

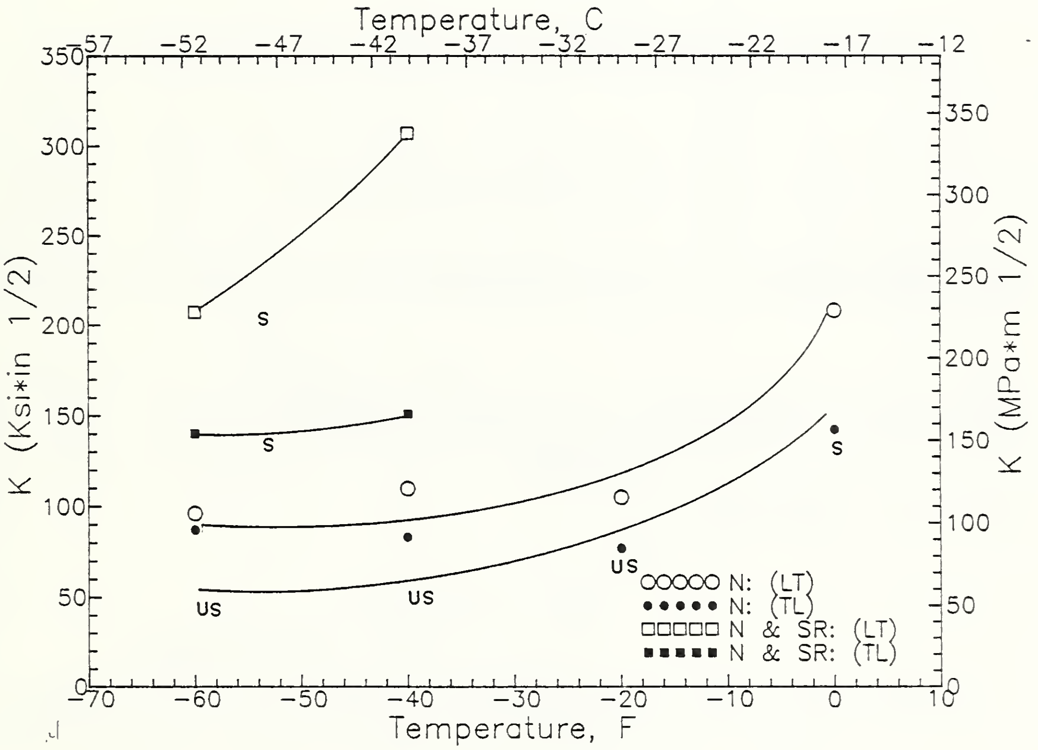


Figure 14. Fracture toughness results, K, as a function of test temperature. The normalized, and normalized and stress relieved steels, and ASTM L-T and T-L orientations are compared. "S" refers to stable crack growth, and "US" to unstable crack growth.

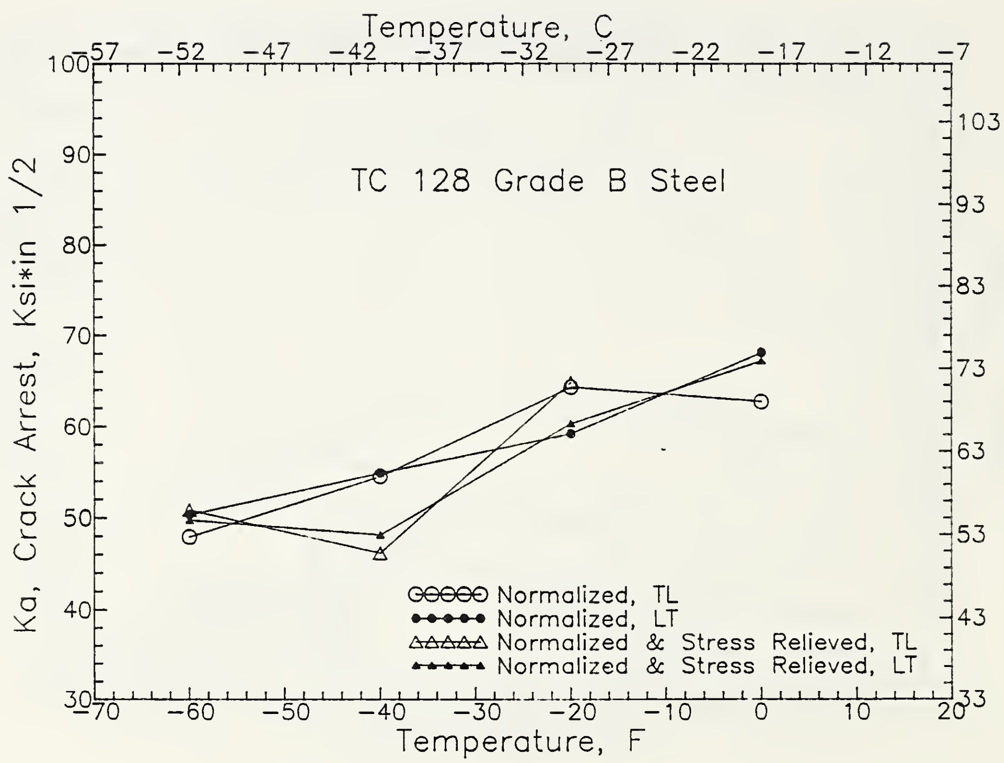


Figure 15. The crack arrest fracture toughness, K_a, as a function of test temperature. The normalized, and normalized and stress relieved material, and ASTM L-T and T-L orientations are compared.

APPENDIX I

BURNS HARBOR PLANT

REPORT OF TESTS AND ANALYSES

SHIPMENT NO.	DATE SHIPPED	CAR OR VEHICLE NO.		PAGE
803-09465	5-9-89	GARY TFR	TRLR 4007	PAGE 2

SOLD TO: UNION TANK CAR CO
151ST & RAILROAD AVE
EAST CHICAGO IN 46312

SHIP TO: UNION TANK CAR CO
151ST & RAILROAD AVE
EAST CHICAGO. IN 46312

SERIAL NUMBER	PAT. NO.	HEAT NUMBER	NO. PCS.	THICKNESS INCHES	WIDTH OR DIA. INCHES	LENGTH INCHES	WEIGHT POUNDS	YIELD POINT PSI	TENSILE STRENGTH PSI	ELONG. IN	ELONG. %
B 10492		803C67159	4	9/16	72	72	3308	58400	83600	8	18
				N 1650	DEG F. -	29 MIN					

QUALITY STEEL MELTED & MANUFACTURED IN THE U. S. A.

PLATES - AAR TC128 GR B FLANGE QUAL REV
9/1/85 --- PLT NORMALIZE
MFST - TRIAL ORDER LIFT MAX 10 TON-SIZES & GRADES SEP
UNLDG OH-PLATE HOOK
CO# 3-47132 GH 021-8706

PLATES HEAT TREATED WITH TEST SPECIMENS ATTACHED AND YIELD STRENGTH @ .5% E.U.L.

Q—QUENCH TEMPERATURE T—TEMPER TEMPERATURE N—NORMALIZE TEMPERATURE

SERIAL NUMBER	PAT. NO.	HEAT NUMBER	HARD	BEND	THICKNESS INCHES	TYPE	SIZE	DIR.	TEST TEMP. F	ENERGY FT. LBS. 1	2	3	SHEAR (%) 1	2	3	LAT. EXP. 1	2	MIL

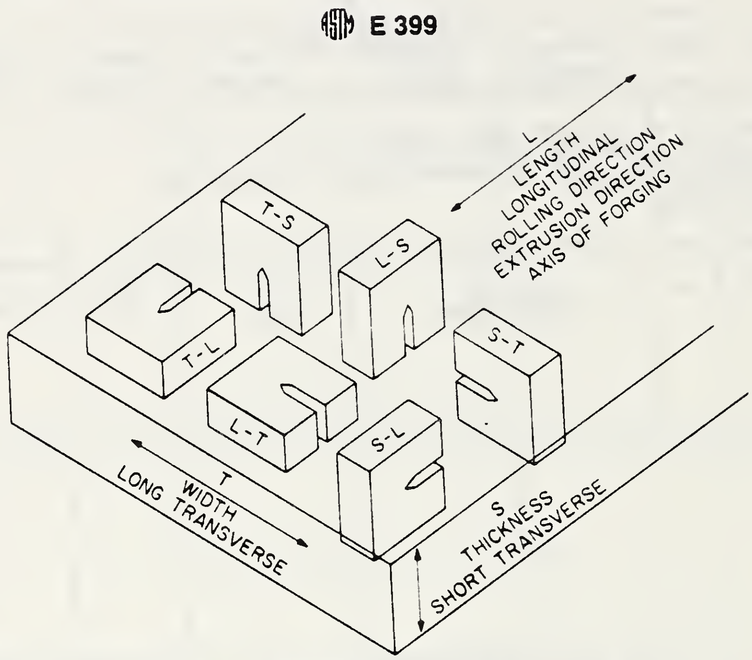
CHARPY IMPACT

CHEMICAL ANALYSIS

HEAT NUMBER	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	Ti	Al	B	Cb	N
803C67159	.22	1.27	.015	.012	.241	.034	.04	.23	.062	.034		.065			

CERTIFY THAT THE ABOVE RESULTS ARE A TRUE AND CORRECT COPY OF RECORDS PREPARED AND MAINTAINED BY BETHLEHEM IN COMPLIANCE WITH THE REQUIREMENTS OF THE SPECIFICATION CITED ABOVE.

SUPT. QUALITY ASSURANCE A. J. BARSOPHY PER PJH



Crack Plane Orientation Code for Rectangular Sections

NIST-114A (REV. 3-90)	U.S. DEPARTMENT OF COMMERCE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY	1. PUBLICATION OR REPORT NUMBER NISTIR 4660
	BIBLIOGRAPHIC DATA SHEET	2. PERFORMING ORGANIZATION REPORT NUMBER
		3. PUBLICATION DATE SEPTEMBER 1991

4. TITLE AND SUBTITLE

Mechanical Properties and Fracture Toughness of AAR TC128 Grade B Steel in the Normalized and Normalized and Stress Relieved Conditions

5. AUTHOR(S)

6. PERFORMING ORGANIZATION (IF JOINT OR OTHER THAN NIST, SEE INSTRUCTIONS)

U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
GAITHERSBURG, MD 20899

7. CONTRACT/GRANT NUMBER

8. TYPE OF REPORT AND PERIOD COVERED

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (STREET, CITY, STATE, ZIP)

10. SUPPLEMENTARY NOTES

11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

Traditional mechanical property tests, ultimate and yield strength, reduction in area, elongation, impact, and the nil-ductility temperature were performed on AAR TC128 grade B in the normalized, and the normalized and stress relieved conditions from -51 C to room temperature. In addition the crack initiation fracture toughness, as function of temperature, was determined using CTOD and J integral test procedures. The crack arrest fracture toughness, as a function of temperature was also determined. It was found that the normalized and stress relieved steel had overall better mechanical and fracture toughness properties than the normalized steel.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

fracture toughness; low temperatures; mechanical properties; normalized; steel plate; stress relieved

13. AVAILABILITY

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14. NUMBER OF PRINTED PAGES

45

15. PRICE

A03

ELECTRONIC FORM